Nitrogen Response in Cotton as Affected by Tillage System and Irrigation Level

K. F. Bronson,* A. B. Onken, J. W. Keeling, J. D. Booker, and H. A. Torbert

ABSTRACT

More than 0.5 million ha of irrigated cotton (*Gossypium hirsutum* L.) are grown in the Southern High Plains of Texas. Conservation tillage cotton in terminated wheat (*Triticum aestivum* L.) has been shown to improve water use efficiency and reduce wind erosion. However, limited N fertilizer response research has been done in this system. The objective of this 3-yr field study at Lubbock, TX was to characterize the response to N fertilizer (0, 28, 56, 84, or 112 kg N ha^{-1}) at varying irrigation levels [0, 25, 50, or 75 % Evapotranspiration (ET) replacement] for conventional and conservation tillage cotton in an Acuff loam (fine loamy, mixed, superactive, thermic, Aridic Paleustoll). Additionally, we tested the chlorophyll meter as an indicator of in-season N status of cotton and compared it to petiole NO_3–N analysis. Cotton lint yields showed a quadratic response to irrigation level in 1996 and 1997, and a linear response in the drought year of 1998. Maximum lint yield varied from 71 to 97 % ET replacement. In 1997 and 1998, cotton lint yields responded to N at the 50 and 75% estimated ET replacement irrigation levels, but not at the 0 or 25% ET levels. Quadratic-plateau models indicated that 19 to 38 kg N additional fertilizer ha^{-1} was needed to produce economically optimum lint yields near 1100 kg N ha^{-1} with conservation tillage than with conventional tillage. Chlorophyll meter and petiole NO_3–N readings were positively related to N rate but were not affected by tillage system.

The Southern High Plains of Texas is the most concentrated area of cotton production in the USA at 1.2 million ha (Texas Agricultural Statistics Service, 1998). This region is characterized by low, erratic rainfall, high winds, and a relatively short growing season. Water, N, and growing season length are the most limiting factors of cotton production in this region where annual rainfall averages 45 cm. About half of the cotton area is *deficit-irrigated* (irrigation input is less than ET). Optimal irrigation amounts are about 75% replacement of estimated ET in the low energy precision application (LEPA) irrigation system [Bordovsky et al., 1992; Agricultural Complex for Advanced Research and Extension Systems, 1997]. Lint yield response to N fertilization, however, is often difficult to predict. In the Southern High Plains, N fertilizer response is strongly linked to water management and to initial soil NO_3^-–N levels (Morrow and Krieg, 1990).

A conservation tillage cotton production system using wheat or rye (*Secale cereale* L.) winter cover, terminated with glyphosate [isopropylamine salt of *N*-(phosphonomethyl) glycine] has gained increased producer acceptance over the past 10 to 15 yr (Lascano et al., 1994; Boyd, 1996). This practice has been shown to have the benefits of minimizing soil evaporation, improving water use efficiency, and reducing wind erosion and wind-blown sand damage to seedlings (Lascano et al., 1994). Conservation tillage cotton in the High Plains can be as productive as and more profitable than conventional tillage cotton (Keeling et al., 1989). A potential disadvantage of this system is in cases of low rainfall springs. Water use by the wheat cover crop can deplete the soil profile of water that otherwise would have been available for the cotton crop.

Irrigated cotton response to N fertilizer in a conservation tillage system has not been well documented in the High Plains region of Texas. Several dryland cotton experiments have been reported in Texas which compared conservation tillage with conventional tillage, but in general these studies did not have N fertilization treatments (Harman et al., 1989; Clark et al., 1996). Liu and Matocha (1996) reported the effects of 4 yr of N fertilization on organic matter dynamics in continuous no-till, dryland cotton in coastal Texas. Varco et al. (1999) examined N fertilizer response in cotton planted into terminated rye in Mississippi.

Nitrogen response of crops such as corn (*Zea mays* L.) and rice (*Oryza sativa* L.) have been monitored with in-season measurements with the chlorophyll meter, which measures greenness of the leaf (Varvel et al., 1997; Hussain et al., 2000). Few studies have tested the chlorophyll meter as an indicator of in-season N status in cotton (Wood et al., 1992; Wu et al., 1998), and none in a semiarid environment. Since evaluating N fertilizer response is a main objective of this study, we hypothesized that in-season chlorophyll meter readings will reflect N nutrition and response. Petiole nitrate has been the most commonly used indicator of in-season N status in cotton (Sabbe and Zelinkski, 1990; McConnell et al., 1993).

The objectives of this study were to (i) Characterize the response of cotton to N fertilizer at varying irrigations levels for conventional and conservation tillage systems and (ii) Compare chlorophyll meter readings with petiole NO_3^-–N as an index of N status in conservation tillage cotton and as an indicator for in-season N fertilizer applications.

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Abbreviations: ET, evapotranspiration; PET, potential evapotranspiration.

Table 1. Analysis of variance of cotton lint yields as affected by tillage system, irrigation rate, and N rate, Lubbock, TX, 1996–1998.

Source of variation	DF†	*F* test 1996	1997	1998
Replicate	2	ns‡	ns	ns
System	1	ns	ns	ns
Replicate × system	2	*	ns	ns
Water	3	**	**	**
Linear	1	**	**	**
Quadratic	1	*	*	ns
Replicate × water	6	ns	ns	ns
Water × system	3	ns	ns	ns
Replicate × water × system	6	ns	*	**
N rate	4	ns	**	**
Linear	1	ns	**	**
Quadratic	1	ns	**	**
N rate × system	4	ns	ns	ns
Water × N rate	12	ns	*	*
Water × N rate × system	12	ns	ns	ns
Residual	64			
CV§ - system %		30.0	15.9	13.6
CV - water %		10.2	19.3	12.8
CV - N rate %		10.3	9.9	6.4

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† Degrees of freedom.
‡ Not significant.
§ Coefficient of variation.

MATERIALS AND METHODS

The study was conducted at the Texas A&M University Research and Extension Center near Lubbock, TX, on an Acuff fine sandy loam with <0.3% slope. The 0- to 15-cm soil had the following properties: 1:1 pH of 7.6, 0.6 g kg^{-1} total N, 5.6 g kg^{-1} total C, 547 g sand kg^{-1}, 171 g clay kg^{-1}, 282 g silt kg^{-1}, 20 and 406 mg kg^{-1} acidified ammonium acetate-EDTA-extractable P, and K, respectively. Since the effective rooting zone of irrigated cotton is considered to be as deep as 90 cm (Zelinski, 1985), additional soil samples to that depth were taken. Initial extractable- NO_3^-–N in the spring of 1996 in the 0- to 90-cm soil profile was 51 kg NO_3^-–N ha^{-1} (based on five subsamples taken from each of the 24 subplots described below).

The experimental design utilized was a split–split plot design with three replications. Main plots consisted of two tillage systems which were randomly assigned within each of the three replications: conservation tillage in wheat residue and conventional tillage with no winter cover crop. The subplots (8, 1-m wide by 75-m long rows) were randomly assigned irrigation levels: 0, 25, 50, or 75% replacement of estimated ET minus rainfall. Rates of N fertilizer were the sub-subplots (8, 1-m wide by 15-m long rows): 0, 28, 56, 84, or 112 kg N ha^{-1}. Nitrogen was applied preplant as a urea-ammonium nitrate solution (320 g N kg^{-1}) by knifing-in 8-cm deep and 15 cm each side of every row center. Cotton planting dates ranged from 4 to 13 May and harvest dates ranged from 30 October to 12 November.

Conservation tillage plots had cotton stalks shredded and plots bedded on 1-m centers. Winter wheat was planted in late November of each year at the rate of 67 kg seed ha^{-1} in 15-cm rows and grown without irrigation. In April of each year, wheat was terminated with glyphosate. Wheat at termination was near the boot stage (Zadoks et al., 1974) and the dry biomass was variable from year to year, ranging from 0.5 to 1.2 Mg ha^{-1}. Conventional tillage plots were shredded, disked, and had trifluralin [2,6-dinitro-*N*, *N*-dipropyl-4-(trifluoromethyl) benzenamine] incorporated with a springtooth harrow prior to bedding for annual weed control. These plots were tilled prior to planting to remove weeds and to shape beds. No tillage was performed in the conservation tillage plots. Since mechanical incorporation was not possible in conservation tillage plots, Metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide and prometryn [*N*,*N*′-bis(1-methylethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine] were applied preemergence for annual weed control. Pyrithiobac {2-chloro-6-[(4,6-dimethoxy-2-pyrimidinyl)thio]benzoic acid} was applied postemergence topicaly to both conventional and conservation tillage plots to control emerged weeds and give late season palmer amaranth (*Amaranthus palmeri* L.) control. Weed escapes were hand hoed as needed during the growing season.

Cotton (cv. Paymaster HS 26) was seeded in early May each year in 1-m rows on top of the beds at a rate of 163 350 seed ha^{-1} (Lascano et al., 1994). Phosphorus was applied to all plots at 22 kg P ha^{-1} in 1996 and 1997 by knifing-in liquid H_3PO_4 (236 g P kg^{-1}) at a 8-cm depth, 15 cm from both sides of the rows before planting, based on the soil test P (acidified ammonium acetate-EDTA-extractable). Soil test P was greater than the critical level of 21 mg kg^{-1} in 1998, so no P fertilizer was applied that year (Texas Agric. Exp. Stn., 1987).

Prior to cotton planting, a furrow irrigation of about 15 cm was applied to insure germination and emergence. The method of in-season irrigation was surface drip delivered through drip tape which was installed after emergence each season on the soil surface in 2-m centers between adjacent cotton rows. The irrigated or wet furrows were diked every 2 m to reduce runoff losses (Lyle and Bordovsky, 1983). Emitter spacing was 50 cm, and emitter flow rate was 2.0 L h^{-1} at 66 000 Pa operating pressure. Frequency of irrigation in the absence of rain was approximately every 3 d. Potential evapotranspiration (PET) was estimated with a modified Penman–Monteith equation from daily weather data (Lascano et al., 1993). Cotton crop coefficients, related to development stages, were used to adjust

Table 2. Rainfall and evapotranspiration (ET) replaced through irrigation, 1996–1998, Lubbock, TX.

	1996	1997	1998
Rainfall, cm			
April	0.1	14.7	1.1
May	5.8	6.8	0.1
June	6.6	7.0	3.9
July	4.2	4.6	0.2
August	15.7	3.8	9.3
September	1.9	4.0	0.3
Preplant irrigation, cm	15.0	15.0	15.0

	1996				1997				1998			
Target ET replacement, %	0	25	50	75	0	25	50	75	0	25	50	75
In-season irrigation, cm	0	9.0	17.8	26.1	0	9.0	17.0	24.6	0	7.8	14.8	22.5
Total, cm	49.3	58.3	67.1	75.4	55.9	64.9	72.9	80.6	29.9	37.7	44.7	52.4

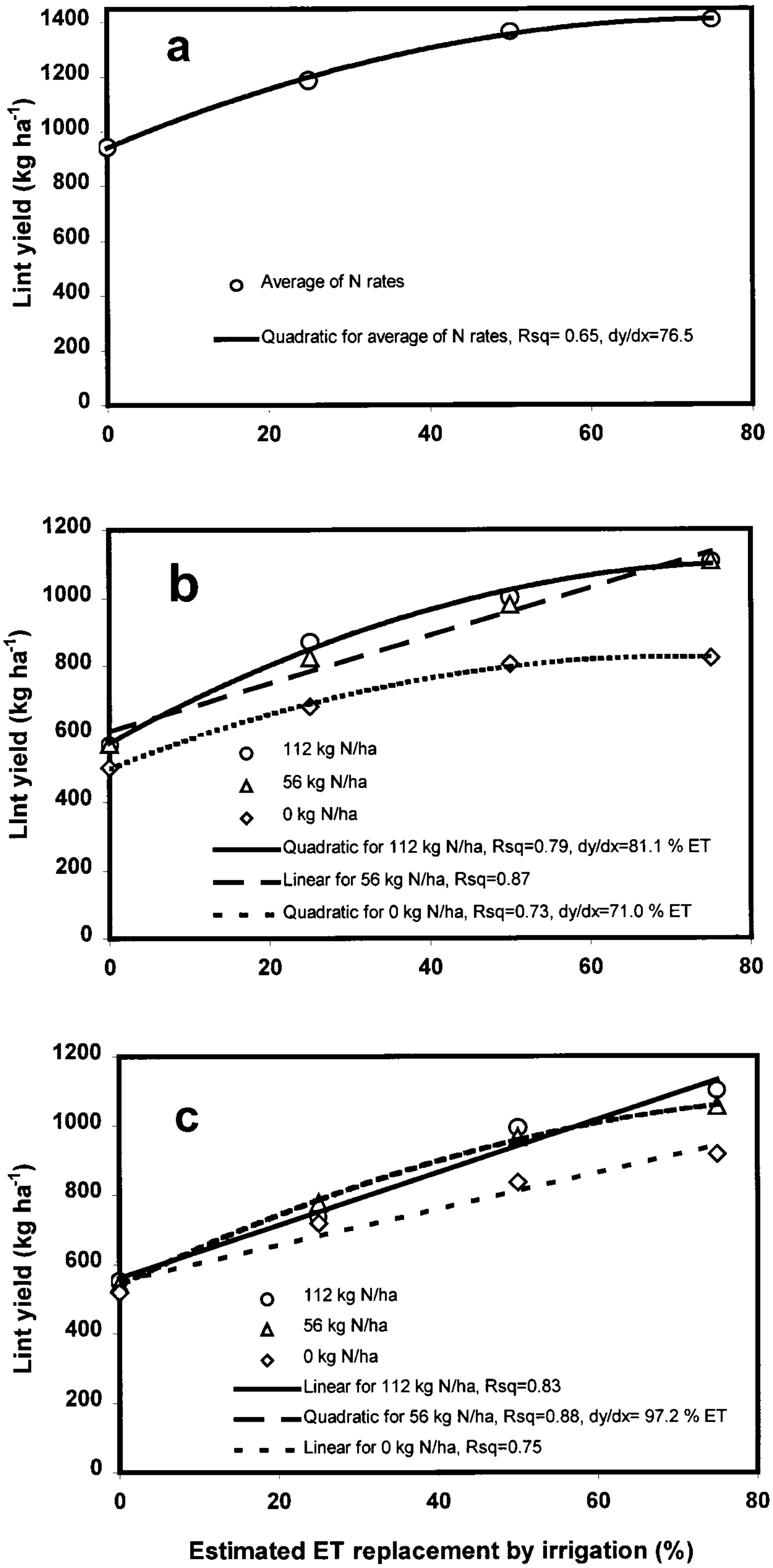

Fig. 1. Lint yield response to irrigation (averaged across tillage system) (a) 1996 (averaged across N rate), (b) 1997 (by N rate), and (c) 1998 (by N rate).

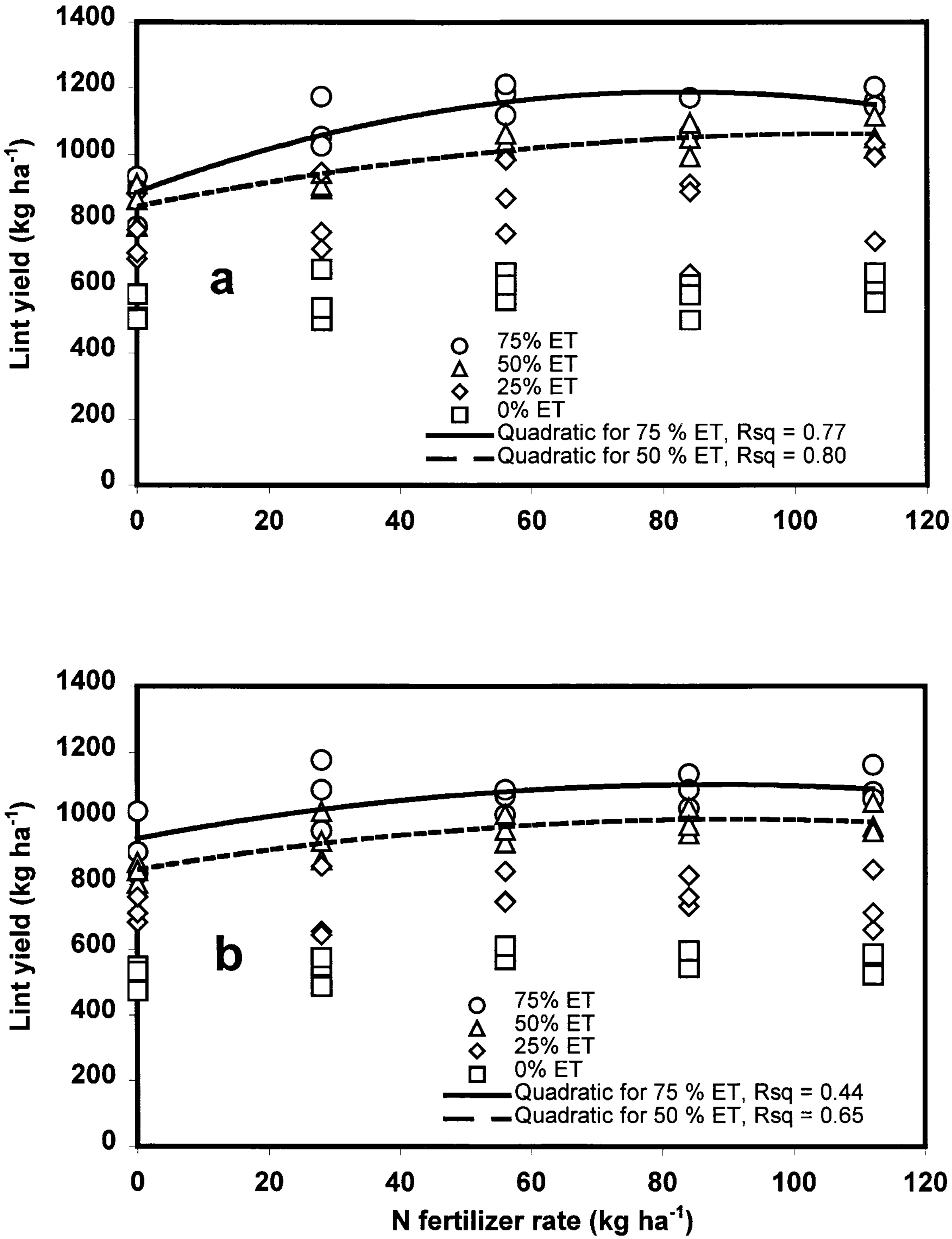

Fig. 2. Lint yield response to N fertilizer by irrigation level (averaged across tillage system) (a) 1997, and (b) 1998.

PET to estimated ET for applying the various ET replacement irrigation treatments (Bordovsky et al., 1992).

Chlorophyll meter readings were taken weekly for 6 to 7 wk from early July (first bloom) to mid August on the 75% ET replacement, conservation tillage plots, at all N levels. One reading was taken from the most recently fully expanded leaf of 20 random plants per plot. In most cases, this leaf was four nodes from the top of the plant. The petioles were removed from the leaves after chlorophyll meter readings were taken. The petioles were oven-dried at 70°C and extracted with 0.1 *M* KCl (400:10) for colorimetric NO_3^-–N analysis with an autoanalyzer (Technicon AutoAnalyzer II, Technicon Industrial Systems, Tarrytown, NY). In 1998, chlorophyll meter readings and petiole NO_3^-–N were determined as before, except they were taken on the 0, 56, and 112 kg N ha^{-1}, 75% ET replacement plots of both tillage systems. Additionally in 1998, the cotton leaves sampled were analyzed for N concentration with a N analyzer (Leco FPS 528, Leco Corporation, St. Joseph, MI). Sufficiency index was calculated as the chlorophyll meter reading of the treatment divided by the

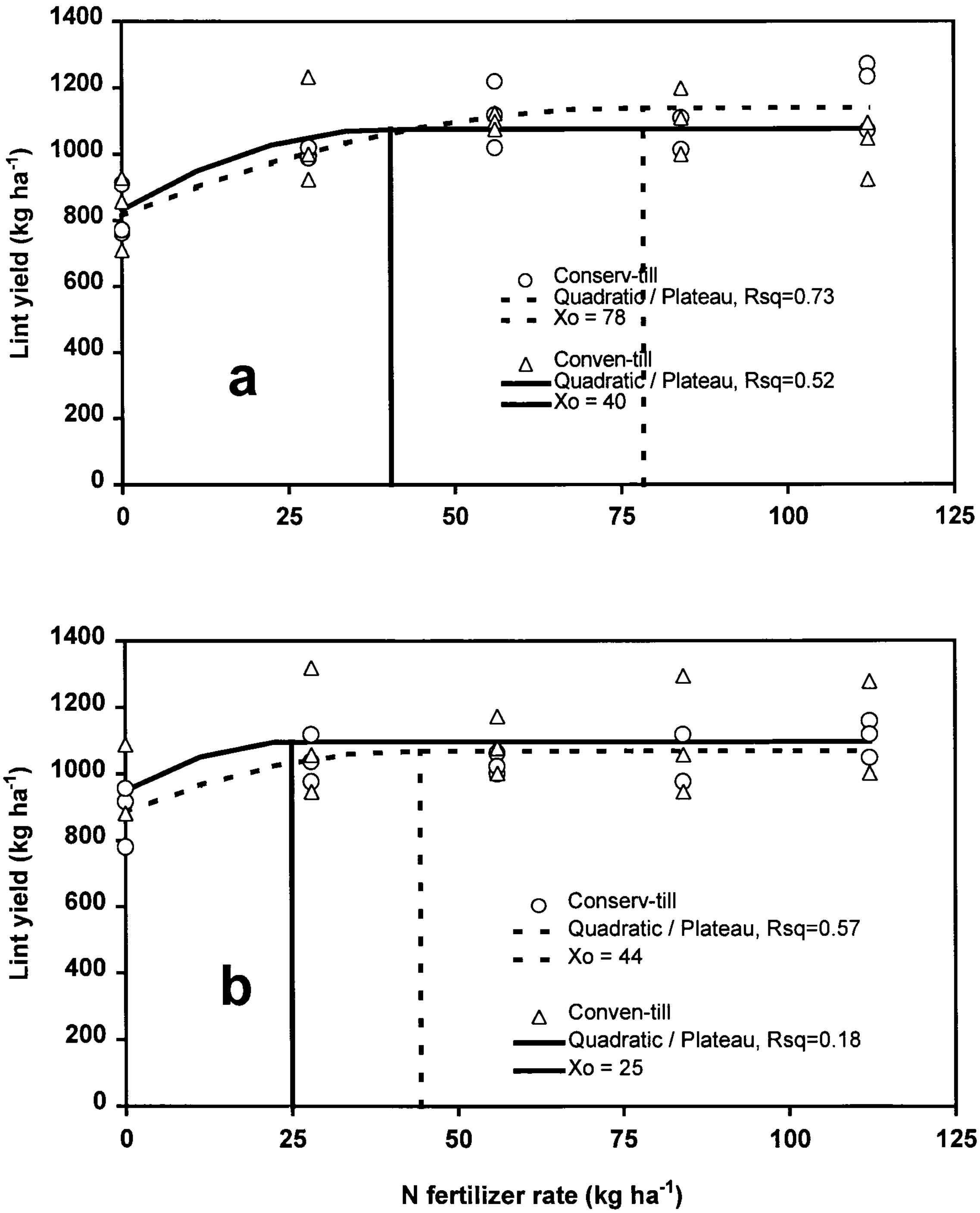

Fig. 3. Optimal Nitrogen fertilizer response of cotton lint yields at 75% evapotranspiration replacement irrigation level by tillage system (a) 1997, and (b) 1998.

average chlorophyll meter reading of the 112 kg N ha^{-1} treatment, similar to Varvel et al. (1997) with corn. The use of the high N rate as the well-fertilized reference for calculating sufficiency index is justified because the optimal N fertilizer rate in terms of lint yield was always less than this rate. Soil samples (0–15-, 15–30-, 30–60-, and 60–90-cm depths) were taken from all plots after harvest each year. Five subsamples from each plot were composited. Soil samples were air dried and extracted with 0.1 *M* KCl (100:10) for colorimetric NO_3^-–N analysis by autoanalyzer.

The center two rows of each 15-m plot were stripper-harvested each year. Seed cotton was ginned and yields are reported as lint.

Statistical analysis consisted of ANOVA of lint yield and soil NO_3^-–N data by year using PROC GLM in SAS for a split–split plot design (SAS, 1996). Lint yield data were fitted to quadratic and quadratic–plateau models (with PROC NLIN in SAS) with N fertilizer rate as the dependent variable for each year and irrigation level within each tillage system as suggested by Cerrato and Blackmer (1990). Economically optimum N fertilizer rates were calculated by setting the first derivative of the quadratic segment of the quadratic–plateau

Table 3. Analysis of variance of chlorophyll meter readings and petiole NO_3^-–N as affected by N rate for conservation tillage cotton, Lubbock, TX, 1996 and 1997.

	1996			1997		
		F test			*F* test	
Source of variation	DF†	Chlorophyll meter	Petiole NO_3^-–N	DF	Chlorophyll meter	Petiole NO_3^-–N
Replicate	2	*	ns‡	2	ns	**
N rate	4	ns	ns	4	**	**
Linear	1	*	ns	1	**	**
Quadratic	1	ns	ns	1	*	ns
Replicate × N rate	8	**	*	8	ns	ns
Date	7	**	**	6	**	**
N rate × date	28	ns	ns	24	*	*
Residual	70			60		
CV§ - N rate, %		9.7	44.3		5.4	16.9
CV - Date, %		4.9	29.9		4.2	18.8

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† Degrees of freedom
‡ Not significant.
§ Coefficient of variation.

model equal to a N fertilizer/lint price ratio of 0.33 ($0.43 kg N fertilizer^{-1} and $1.32 kg lint^{-1}). Cotton yields were also fitted to quadratic or linear models with irrigation level as the dependent variable; plateau models did not fit this data. Optimal (agronomic maximum) irrigation levels were likewise calculated by setting the first derivative of the quadratic response functions to zero without using price ratios. Chlorophyll meter readings and petiole NO_3^-–N data were analyzed by year with a repeated measures (date) term in the ANOVA model. Simple correlation between chlorophyll meter readings and petiole NO_3^-–N (and leaf N in 1998) was done by year and by date.

RESULTS AND DISCUSSION

Cotton Lint Yield

Cotton lint yields responded to irrigation levels in all three years of the study (Table 1). Figure 1a shows the irrigation response in 1996, which is averaged across N rates because there was no N by irrigation interaction. Irrigation response by N rates (0, 56, and 112 kg N ha^{-1} shown in Fig. 1b,c) in 1997 and 1998 were either linear or quadratic. In the drought year of 1998, averaged across all N rates and tillage, the response to irrigation was linear (Table 1).

The optimal irrigation levels could only be calculated for the quadratic functions in Fig. 1. These ranged from 71 to 97% ET replacement. Irrigation replacement of 75% of estimated ET often results in optimal cotton production in the Southern Plains (Agricultural Complex for Advanced Research and Extention Systems, 1997). Irrigation at 100% ET can result in excessive vegetative growth and delayed crop maturity (Bordovsky et al., 1992). The 0% ET lint yields in 1996 were 370 kg ha^{-1} greater than in 1997 or 1998 (Fig. 1). The reason for these overall greater yields in 1996 compared to 1997 are not apparent from the rainfall records (Table 2). Nearly 15 cm of rain fell in April (the month before planting) in 1997, while just a trace fell in April, 1996. In-season rainfall, on the other hand, was slightly lower in 1997 than in 1996. Overall, April to September rain was near normal, and rain plus irrigation was not much different between the two years. In 1998, however, rain from May through July was very low (Table 2), which

Table 4. Analysis of variance of cotton chlorophyll meter readings, petiole NO_3^-–N and leaf N content as affected by tillage system and N rate, Lubbock, TX, 1998.

		F test		
Source of variation	DF†	Chlorophyll meter readings	Petiole NO_3^-–N	Leaf N
Replicate	2	ns	ns	ns
System	1	ns	ns	ns
Replicate × system	2	**	**	**
N rate	2	**	**	**
Linear	1	**	**	**
Quadratic	1	ns	ns	ns
N rate × system	2	ns	ns	ns
Replicate × N rate × system	8	ns	ns	**
Date	5	**	**	**
N rate × date	10	*	**	*
Date × system	5	**	ns	ns
N rate × date × system	10	ns	ns	ns
Residual	60			
CV§ - system, %		19.0	145	22.9
CV - N rate, %		2.8	41.0	6.4
CV - date, %		2.4	31.3	3.1

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† Degrees of freedom.
‡ Not significant.
§ Coefficient of variation.

Table 5. Petiole NO_3^-–N of conservation tillage cotton as affected by N fertilizer rate, Lubbock, TX 1996–1998.

	N fertilizer rate					N rate	
	0	28	56	84	112	*F* test	CV†
	g N kg^{-1}						
1996							
First bloom	12.5	17.4	14.3	14.4	13.8	ns‡	18.2
5 wk after first bloom	0.1	0.1	0.1	1.1	1.4	ns	58.2
1997							
First bloom	11.7	17.8	18.7	19.7	18.6	*	6.4
5 wk after first bloom	2.8	2.0	2.5	2.4	3.6	ns	30.3
1998							
First bloom	8.4	ND§	12.0	ND	13.6	**	13.6
5 wk after first bloom	1.8	ND	2.6	ND	2.5	ns	30.8

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† Coefficient of variation.
‡ Not significant.
§ Not determined.

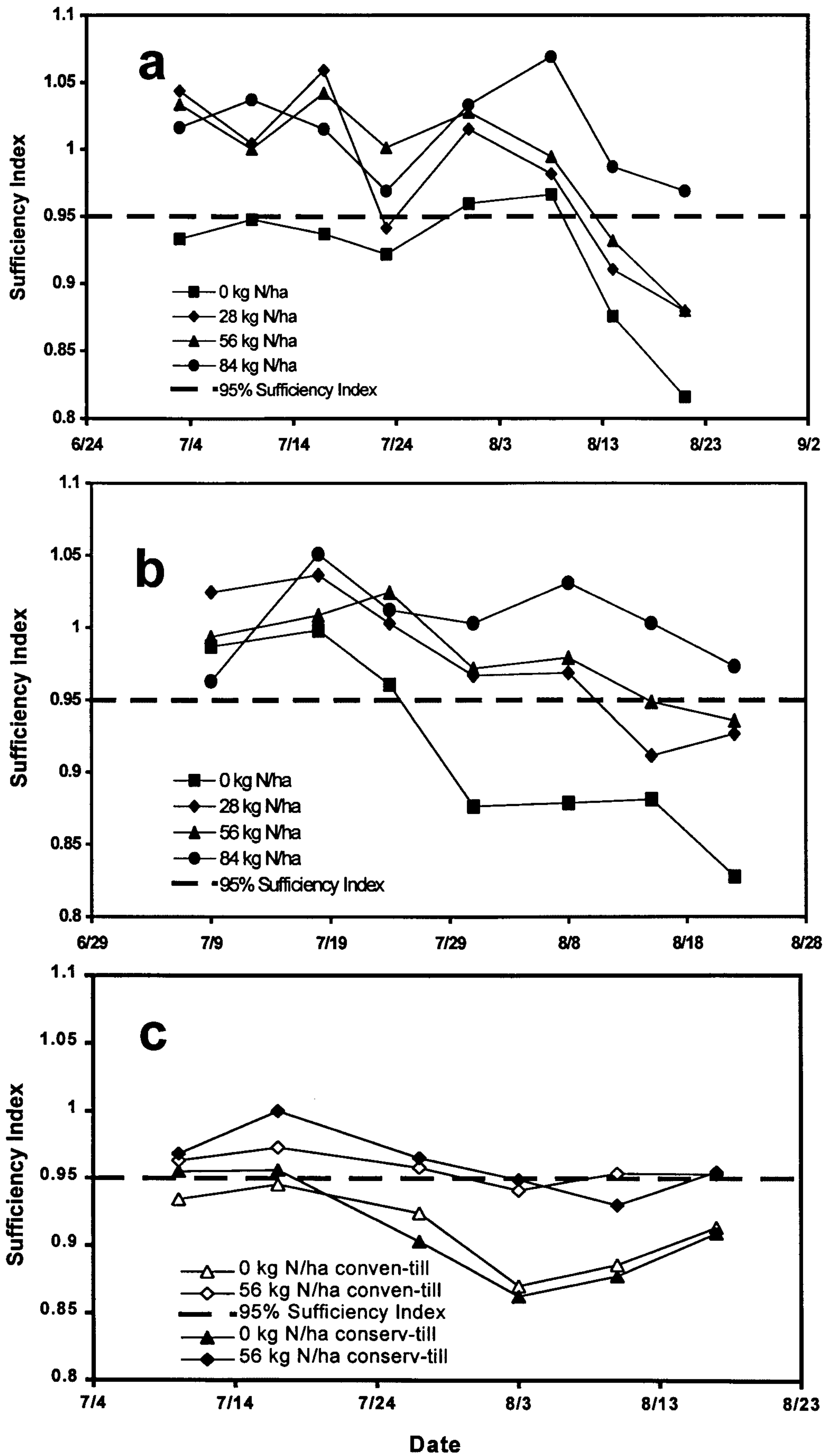

Fig. 4. Chlorophyll meter sufficiency indices of conservation tillage cotton as affected by N fertilizer rate (a) 1996, and (b) 1997; (c) 1998, conventional and conservation tillage.

Table 6. Correlations between cotton lint yields, chlorophyll meter readings, petiole NO_3^-–N, and leaf N, 1996–1998, Lubbock, TX.

	First bloom				5 wk after first bloom			
	Lint yield	Chlorophyll meter	Petiole NO_3^-–N	Leaf N	Lint yield	Chlorophyll meter	Petiole NO_3–N	Leaf N
			1996					
Lint yield	–	ns†	0.55*		–	0.52*	0.62*	
Chlorophyll meter readings		–	ns			–	ns	
Petiole NO_3^-–N			–			–		
			1997					
Lint yield	–	ns	ns		–	0.59*	0.67**	
Chlorophyll meter readings		–	ns			–	0.73**	
Petiole NO_3^-–N			–			–		
			1998					
Lint yield	–	ns	0.53*	0.48*	–	ns	ns	0.50*
Chlorophyll meter readings		–	0.76**	0.70**		–	0.57**	0.60**
Petiole NO_3^-–N			–	0.81**			–	0.84**

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† Not significant.

explains the lower yields and the linear response of cotton to irrigation that year (Fig. 1c).

The main effect of tillage system on lint yields was not significant (Table 1). This is similar to the results of Keeling et al. (1989) who reported similar lint yields between conventional and conservation tillage in terminated wheat. Economically, conservation tillage cotton farmers may profit more without increasing yields if their costs, such as tillage, are reduced. In dryland cotton in the Texas rolling plains, on the other hand, greater cotton lint yields were reported with no tillage (without terminated wheat) vs. conventional tillage (Clark et al., 1996). The interaction of tillage system × water in our study was not significant. It could be concluded from the lack of system and system × water effects that water use efficiency was unchanged with conservation tillage compared to conventional tillage. However, tillage system × N rate interaction was significant in 1997 and 1998 (Table 1), and therefore the net effect of tillage × N rate interaction and water use efficiency on lint yields must be considered.

Lint yield response to N fertilizer was absent in 1996 but was evident in 1997 and 1998 (Table 1, Fig. 2). However, the sum of squares for 1997 and 1998 associated with water in the ANOVA were larger than for N fertilizer rate (not shown), indicating the greater importance of water in controlling cotton production compared to N. The reason for a lack of response to N fertilizer in the first year at the high irrigation levels may be related to the site history, which was in corn for the previous two years. Corn was fertilized with 112 kg N ha^{-1}, and was furrow irrigated and conventionally tilled. Grain yields of corn ranged from 4 to 5 Mg ha^{-1}. Nitrogen mineralization in corn residue, in addition to the initial 51 kg residual soil NO_3^-–N ha^{-1}, may have precluded a N fertilizer response in 1996. Greater indigenous N supply in 1996 may explain the greater yields at all irrigation levels mentioned above.

In 1997 and 1998 response of cotton to N fertilizer was greatest at the 75% ET irrigation level, significant, but weaker at the 50% ET water level, and absent at the 0 and 25% ET levels (Fig. 2). The lack of response to N fertilizer in the zero in-season irrigation treatment (dryland) indicates that the initial levels of exchangeable NO_3^-–N of 51 kg ha^{-1} in the 0- to 90-cm depth and net N mineralization of soil organic matter and crop residues were sufficient to achieve the lower yield potential of the dryland soil moisture regime. Morrow and Krieg (1990) also reported greater response to N fertilizer in cotton at high ET replacement compared to dryland cotton grown in the Texas High Plains.

Economic Optimum Nitrogen Fertilizer Rates

We calculated the economically optimum N fertilizer rate from quadratic–plateau models. The optimal agronomic level of N fertilizer calculated from these models is usually much less than with quadratic models and is often close to the economic optimum (Cerrato and Blackmer, 1990). In both 1997 and 1998, the optimal N fertilizer rates at 75% ET irrigation level was greater with conservation tillage cotton (78 and 44 kg N ha^{-1} in 1997 and 1998, respectively) than with conventional tillage cotton (40 and 25 kg N ha^{-1}, in 1997 and 1998, respectively, Fig. 3). Economically optimum lint yields were about 1100 kg ha^{-1} in 1997 and 1998. Greater N requirement with conservation tillage cotton was probably the result of early season immobilization of N by microorganisms involved in the decomposition of the wheat residue (Doran and Smith, 1987). Similar to our results, Varco et al. (1999) reported higher N fertilizer requirements in no-tillage cotton in Mississippi following a paraquat-terminate rye winter cover crop compared with winter fallow. Our results also suggest that alternative timing of N fertilizer application, such as split applications, may need to be tested. It may be possible, for example, to apply the same total N rates to both cotton tillage systems, but provide a larger fraction at planting in the conservation tillage. Additional N fertilizer may not be needed in a conservation tillage cotton system after a few more years, as several long-term studies cite greater N mineralization in reduced tillage cotton compared to conventional tillage (Liu and Matocha, 1996; Salinas-Garcia et al., 1997).

The apparent increase in N fertilizer requirements in conservation tillage cotton compared to conventional tillage cotton may mask any gains in water use efficiency in terminated-wheat cotton in this study. Lascano et al. (1994) directly measured ET in a study that showed less soil evaporation losses (though similar ET), and thus improved water use efficiency, in conservation tillage terminated wheat cotton compared to conventional tillage.

Chlorophyll Meter Readings and Petiole Nitrate

Chlorophyll meter readings were positively affected by N fertilizer rate all 3 yr of the study (Table 3 and 4), and petiole NO_3^-–N was positively related to N rate in 1997 and 1998 at first bloom only (Table 3, 4, and 5). However, the coefficients of variation were higher for petiole NO_3^-–N than with chlorophyll meter readings, which would have implications for precision and reliability of use as N-status indicators. Chlorophyll meter readings were slightly less variable than leaf N, which was measured only in 1998 (Table 4). Chlorophyll meter readings were higher with conventional tillage cotton from 3 to 17 August for the 112 kg N ha^{-1} rate compared with conservation tillage cotton in 1998 (data not shown). This trend was not observed in the petiole NO_3^-–N or leaf N data. The sufficiency index calculations for chlorophyll meter readings in 1998 were referenced to the 112 kg N ha^{-1} rate within each tillage system.

Petiole NO_3^-–N levels at first bloom were above the suggested deficiency level of 9 g kg^{-1} (Sabbe and Zelinski, 1990) at all N rates in 1996 and 1997, and in all but the zero fertilizer treatment in 1998 (Table 5). Five weeks after first bloom petiole NO_3^-–N concentrations were very low and not related to N rate. This growth stage is about the latest a producer would apply N, but petiole analysis may not be useful at this late stage. Chlorophyll meter readings, on the other hand, were still sensitive to N rate at that time (Fig. 4). Petiole NO_3^-–N and chlorophyll meter readings were not correlated in 1996 at either first bloom or 5 wk later (Table 6). The two measures were correlated at 5 wk after first bloom in 1997 and 1998 and at first bloom in 1998 (Table 6). Correlations between lint yield and either chlorophyll meter readings or petiole NO_3^-–N were not consistent, similar to the report of Wood et al. (1992).

Sufficiency indices from the chlorophyll meter readings during the 7-wk periods of readings decreased to <95% in only a few cases, mostly with the zero N fertilizer rate (Fig. 4a,b). In Table 7, we statistically compared the lint yield of each N fertilizer treatment to the 112 kg N ha^{-1} treatment. Table 7 also indicates whether sufficiency indices were greater than or less than 0.95. Ten of the 12 cases and treatments, chlorophyll meter sufficiency indices of 0.95 prior to 1 wk after first bloom successfully predicted whether lint yield was statistically similar to or different from the highest N rate treatment. There was one exception each in 1996 and in 1997. In 1996 in conservation tillage cotton the sufficiency index dropped below 0.95 for the 0 kg N ha^{-1} rate, but a depression in lint yield from the level of the highest N rate was not observed. The sufficiency index for the

Table 7. Single degree of freedom contrasts for N fertilizer treatments by tillage system for 75% evapotranspiration (ET) irrigation level and corresponding sufficiency indices deviations from 0.95 1 wk after first bloom, Lubbock, TX, 1996–1998.

N fertilizer treatment comparison	1996 Contrast for yield	1996 Chlorophyll meter Sufficiency index relative to 0.95	1996 Petiole NO_3^-–N Sufficiency index relative to 0.95	1997 Contrast for yield	1997 Chlorophyll meter Sufficiency index relative to 0.95	1997 Petiole NO_3^-–N Sufficiency index relative to 0.95	1998 Contrast for yield	1998 Chlorophyll meter Sufficiency index relative to 0.95	1998 Petiole NO_3^-–N Sufficiency index relative to 0.95
N0† vs. N112 cons-till	ns‡	<§	<	**	<	<	**	<	<
N28 vs. N112 cons-till	ns	>§	>	*	>	>	ns	–	–
N56 vs. N112 cons-till	ns	>	>	ns	>	>	ns	>	<
N84 vs. N112 cons-till	ns	>	>	ns	>	>	ns	–	–
N0 vs. N112, conv-till	ns	–¶	–	*	–	–	*	<	<
N28 vs. N112, conv-till	ns	–	–	ns	–	–	ns	–	–
N56 vs. N112, conv-till	ns	–	–	ns	–	–	ns	>	>
N84 vs. N112, conv-till	ns	–	–	ns	–	–	ns	–	–
#CV, %	10.3			9.9			6.4		

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† N followed by a number indicates N fertilizer rate in kg N ha^{-1}.
‡ Not significant.
§ <, >, less than and greater than, respectively.
¶ – not determined.
# Coefficient of variation.

Table 8. Analysis of variance of residual soil NO_3^-–N (0–90 cm) in 1998 as affected by 3-yr tillage system, irrigation rate, and N rate, Lubbock, TX.

Source of variation	DF†		*F* test
Replicate	2		ns‡
System	1		ns
Replicate × system	2		ns
Water	3		*
Linear	1		**
Quadratic	1		ns
Replicate × water	6		ns
Water × system	3		ns
Replicate × water × system	6		ns
N rate	4		**
Linear	1		**
Quadratic	1		ns
N rate × system	4		ns
Water × N rate	12		*
Water × N rate × system	12		ns
Residual	64		
CV§ - system %		55.1	
CV - water %		45.3	
CV - nitrogen %		37.4	

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† Degree of freedom.
‡ Not significant.
§ Coefficient of variation.

28 kg N ha^{-1} treatment in conservation tillage in 1997 remained above 0.95 yet a significant lint yield depression was observed. The sufficiency index approach was successful nine of 12 case and treatments when applied to the petiole NO_3^-–N data (Table 7). The leaf N data in 1998 was also used to calculate a sufficiency index and its prediction rate was three of four cases, the same as the petiole NO_3^-–N data in that year (Table 7). The 0.95 sufficiency index based on chlorophyll meter readings, or petiole NO_3^-–N data, therefore has potential to predict need for in-season N fertilizer applications in cotton irrigated at the 75% ET level in the High Plains of Texas. The chlorophyll meter has the advantage of immediate results, compared to the several day turnaround time for petiole NO_3^-–N analysis.

Residual Soil Nitrate and Total Soil Nitrogen

Residual NO_3^-–N in the 0- to 90-cm soil increased in nearly all treatments by the end of the 3-yr study from the original 51 kg NO_3^-–N ha^{-1} (Table 8 and 9). The exceptions were the 0 kg N ha^{-1} treatments, which averaged 64 kg NO_3^-–N ha^{-1}. The difference of 13 kg NO_3^-–N ha^{-1} is less than the LSD of 18.6 kg NO_3^-–N ha^{-1} (0.05 level of probability, 24 plots). Nitrate–N increased with increasing N fertilizer rate, most markedly in the 0 and 25% ET irrigation treatments. In these limited water treatments, the N requirements of the low yielding cotton were met by residual NO_3^-–N and soil N mineralization at the 0 or 28 kg N fertilizer ha^{-1} rates. Apparently much of the N applied above this rate remained in the soil profile as NO_3^-–N. Potentially, some of this residual NO_3^-–N can leach below the root zone of cotton, especially during high rainfall events in the off-season.

Table 9. Residual soil NO_3^-–N (0–90 cm) in 1998 as affected by 3-yr tillage system, irrigation rate, and N rate, Lubbock, TX.

Irrigation level (% ET† replacement)	N fertilizer rate 0	28	56	84	112
	kg NO_3^-–N ha^{-1}				
0	63.0d‡	97.4cd	164ab	193a	209a
25	66.8d	66.9d	103cd	173ab	202a
50	66.9d	77.3d	74.8d	134bc	136bc
75	59.5d	69.2d	87.1cd	99.0cd	110cd

† Evapotranspiration.
‡ Means in all four columns followed by the same letter are not significantly different at the 0.05 level of probability by Duncan's Multiple Range Test.

The effects of tillage system on residual NO_3^-–N was not significant. Although the optimal N fertilizer rate was higher in conservation than in conventional tillage cotton, this was not reflected in the NO_3^-–N data, as the most evident increases in NO_3^-–N were at N rates above the optima. However, annual build up of soil NO_3^-–N does help explain why the optimal amounts of N fertilizer declined in both tillage systems between 1997 and 1998, i.e., cotton is less responsive to N fertilizer with increasing soil NO_3^-–N.

Mineralization of wheat residue N was not evident in the residual soil NO_3^-–N data, although we can assume that a small amount of straw N probably remained in the soil each year. Mineralization of soil organic matter and recycling of crop residue was apparently about 50 kg N ha^{-1} yr^{-1}. This estimate is based on an N utilization efficiency of 10 kg lint kg plant N^{-1} reported by Basset et al. (1970) and the 500 kg lint ha^{-1} yields in the dryland, zero-N plots, where soil NO_3^-–N did not significantly change. This is similar to the results of a 17-yr long term irrigated cotton study in Oklahoma, where zero-N plots averaged 519 kg lint ha^{-1} and 78 kg NO_3^-–N ha^{-1} remained in the 0- to 90-cm soil depth (Westerman and Boman, 1989). Nitrate–N concentrations in the irrigation water were not monitored regularly during our study, but when measured were <10 mg NO_3^-–N L^{-1}.

Total soil N did not change after the 3-yr study. There were likewise no effects of irrigation, tillage, or N rate on total soil N. Longer term studies of this conservation tillage cotton system could show build up of total soil N, and as stated earlier, a reversing of the trend we observed of an increase in N fertilizer needs for conservation tillage terminated-wheat cotton.

SUMMARY AND CONCLUSIONS

Cotton lint yields responded quadratically to irrigation in 1996 and 1997. Irrigation response was linear in the drought year of 1998. Nitrogen fertilizer response in cotton was greatest at the highest irrigation levels compared to low irrigation or dryland. Economically optimum N fertilizer rates were greater in conservation tillage than in conventional tillage. The effect of tillage on water use efficiency could not be established, because of the increase in N fertilizer needs in the conservation tillage system. Residual soil NO_3^-–N accumulated to high levels in the low irrigation, high N fertilizer treatments, but remained stable in the high irrigation, low N treatments. The chlorophyll meter was shown to have potential in predicting need for in-season N at the 75% ET irrigation level, comparable to petiole NO_3^-–N analyses. The current N fertilizer recommendations for cotton in the Southern Plains are based on a combination of a soil NO_3^-–N test and a yield goal, which is dependent on irrigation water availability. In-season monitoring of cotton N status, such as with the chlorophyll meter, could be useful for predicting need of N applications, since it should account for N dynamics such as NO_3^-–N leaching, N immobilization in residue, and N mineralization of soil organic matter that are not predicted by a spring soil NO_3^-–N test.

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